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ERT investigation on horizontal and vertical counter-gravity slurry flow in pipelines

Y. Faraj a*, M. Wang

Univ. Leeds, Institute of Particle Science and Engineering, Clarendon Rd, LS2 9JT, Leeds, UK

Abstract

The occurrence of separation and slippage of the two phases in settling solid-liquid flow in pipelines make the flow unpredictable and time dependent. Therefore it is paramount for the operator of slurry pipelines to monitor and measure the flow continuously, particularly from the local point of view. This paper reports the laboratory experiments carried out on an open flow loop and the use of Electrical Resistance Tomography (ERT) to interrogate the internal structure of horizontal and vertical counter-gravity slurry flow. The use of high performance dual-plane ERT system, which is called Fast Impedance Camera System (FICA), is attempted for fast impedance measurement of the media with a temporal resolution up to 1000 dual-frames per second (dfps). The internal images of the pipeline are captured along with the measurement of solids volumetric concentration for both orientations, while the dual-plane ERT is combined with cross-correlation technique to estimate axial solids velocity distribution. A set of experiments was carried out on coarse and medium sand-water slurry flow with 2% and 10% throughput volumetric concentration and the transport velocity range of 1.5-5 m/s. A flow diversion technique was used for validation of mean local solids concentration and solids axial velocity obtained from the ERT.

Keywords: Settling slurry; horizontal pipe flow; vertical upward flow; Dual-plane electrical resistance tomography; ERT system; cross-correlation

* Corresponding author. Tel.: +44- 113- 343-2358; fax: +44-113- 343-2384.
E-mail address: pm08yf@leeds.ac.uk.

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1. Introduction

Settling slurry flow in pipeline is encountered in many industries such as energy, chemical, pharmaceutical, petroleum, wastewater processing and mining industry. It is worth mentioning that in some specific applications, such as dredging, hydraulic transport is the only mean of transportation of solids through pipelines. These mixtures are transported through different pipeline orientations, mainly horizontal and vertical. It is a very complex flow and has attracted considerable attention of many investigators across the world. A wide range of experimental results have been reported in the literature including different operating conditions, material type and shape and different flow orientations. In horizontal flow as the gravity acts at right angle to the flow, the separation of phases occurs and gives rise to several flow regimes, pseudo-homogeneous, heterogeneous, moving bed and stationary bed. The description of each flow regime is detailed in literature [1, 2, 3, 4]. Whereas in vertical flow, especially upward flow, the gravity acts counter to the dynamic forces, as a result the slippage of the phases occurs [5]. The occurrence of separation and slippage of the constituent phases in settling solid-liquid flow in both horizontal and vertical pipelines makes the flow unpredictable and time dependent. Therefore it is paramount for the operator of these pipelines to monitor and measure the flow continuously, particularly from the local point of view, i.e. the knowledge of internal structure of flow is necessary, so as to ensure safe transport and maintaining acceptable control limits. In order to understand the internal structure of such flows solids volume fraction and solids velocity distribution are of great importance. Therefore, this study focuses mainly on qualitative and quantitative measurement of these two parameters.

In the past, several intrusive methods, such as traditional probes, have been used to measure solids volumetric concentration and velocity. The disadvantages of using these probes have been reported, particularly for solid-liquid flow [6]. It is highly unlikely that these devices can survive the harsh condition inside the pipelines due to abrasive nature of slurry. In many cases solids may accumulate around them and cause pipe blockage. Also it is well known that intrusive devices introduce an undesirable physical disturbance and alter the internal structure of the flow [7]. In order to overcome this limitation, researchers across the world developed a variety of non-intrusive measurement techniques to highlight the internal characteristics of two or multiphase flows, such as optical, ultrasound, nuclear, conductance and electrostatic transducers. Nonetheless, each of the above techniques suffers from serious limitations, especially for solid-liquid flows. For example, since slurries are opaque and flow through opaque enclosures, then using optical techniques can be quite difficult if not impossible. Although nuclear techniques provide an accurate measurement, they are very expensive and suffer from low temporal resolution and environmental issues [8]. Amongst all of the above techniques Electrical Resistance Tomography (ERT), as one of the family of non-intrusive sensors, has attracted the interest of many researchers. This is due to the fact that the ERT offers many advantages, such as non-intrusive, relatively low cost, no environmental restrictions, providing quantitative and qualitative on-line measurement, fast etc. Within the last two decades the ERT has seen a significant development and has been applied to many industrial process involving two/multiphase systems. Particularly the application of the ERT to solid-liquid flow has been reported by many investigators [9, 10, 11, 12, 13, 14]. All of the above studies have been carried out on vertical and/or horizontal flows used the conventional ERT system, which acquires up to 200 images per second [15]. To the authors' knowledge no attempt has been made to measure solids volume fraction and solids axial velocity using the combination of high performance ERT system in conjunction with cross-correlation technique. It is evident that measurement of the two parameters, especially velocity, in fast evolving processes requires high frame rates (fast) of milliseconds. Therefore, this study uses a high performance dual-plane electrical resistance tomography system, which is called Fast Impedance Camera System (FICA) and is capable of acquiring data at a rate of 1000 dual-frames per second (dfps). As horizontal and vertical sections jointly make most of the pipelines, it is important to study both orientations simultaneously with similar conditions, so as to reveal the effect of one on another. However, in higher velocities (pseudo-homogeneous) there may be higher degree of similarities in the internal structure of the flow in the two orientations, but the differences could well be noticed for the transport velocities below the deposition velocity.

This paper reports the application of high temporal resolution ERT in conjunction with cross-correlation technique, to measure and monitor volumetric concentration and characteristic parameters of the dispersed phase (solids velocity) in sand-water flow. The ERT measurements were performed on horizontal and vertical counter-gravity flow simultaneously and are demonstrated qualitatively and quantitatively. It also reveals further information on flow characteristics of both constituent phases at different operating conditions, including two throughput concentrations (2% and 10%) and two non-uniform shape and size sand (medium and coarse). A diversion flow technique was employed for comparing and validation of the ERT measurements. Error analysis has been carried out and the results are shown qualitatively and quantitatively.

2. Experimental set up and procedure

2.1. High performance ERT system

The ERT is an imaging technique and has been widely applied within the last decade by many researchers on various industrial processes; mixing, separation, two/multiphase flow system and reactor vessels [10, 9, 5]. It has been referred to as a soft-field tomographic system. In other words, if an electric current is injected into the medium under investigation, then the distribution of that electric field is determined by the physical electrical properties of that material. It has a non-linear behavior which imposes some difficulties on the image reconstruction, and that is due to the sensitivity of the measurement within a volume, variation of the sensitivity across the nominal sensing zone and sensitivity for a particular position within this region [16]. The ERT is normally used to interrogate the internal structure of a process under investigation by injecting an alternating current (typically 15 mA) and measuring the voltage difference, which is then converted to conductivity. A typical ERT system is composed of three main parts; the ERT sensor, data acquisition system and the image reconstruction system (host computer) [17, 15], as shown in Figure 1.

The full ERT system in house built (Online Instrumentation Laboratory/University of Leeds/UK). The ERT sensor was configured as dual plane sensor in order to apply cross-correlation and measure the local axial velocity of the dispersed phase. 16 stainless steel electrodes were mounted on each plane at equal interval, flush with the inner surface of the pipe, where non-intrusively in contact with the media. The configuration of the electrodes was based on the adjacent protocol, which produces $n(n-3)/2$ measurements (n denotes the number of electrodes). The measurement principle of adjacent strategy is that an alternating current is injected through a pair of adjacent electrodes and the potential difference is measured between the remaining pairs of adjacent electrodes until the full rotation is complete. Based on the adjacent strategy, the number of independent differential voltage measurements for 16 electrodes is 104 measurements [15, 18].

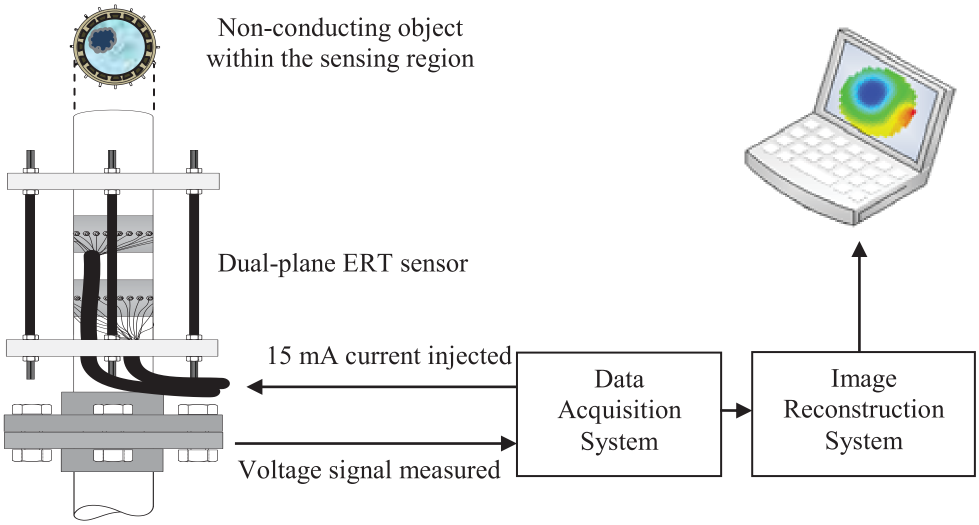

Fig. 1. The structure of a typical electrical resistance tomography system

The inner diameter of each plane was designed to be equal to that of upstream and downstream of the sensor (i.e. the PVC clear pipe sections), so as to allow a smooth inner pipe surface and no interference with the flow. On each plane the same electrodes were used as both current source and voltage detector, which uses adjacent strategy. The electrodes were designed in order to achieve an optimum shape, in which the relationship between the width of the electrode and gap size is 2:1 for the adjacent measurement strategy. The design of the electrodes was based on the design criteria described in [17, 18]. The two planes were separated by an axial distance of 30 mm and mounted on a flanged (PVCu Full Face Flange Drilled BS EN1029-1 PN16 Plain 2") clear PVC pipe sections (50 mm ID). The distance between the electrodes of one plane to the other plane was 70 mm, which was used in cross-correlating the signals of the two planes. The schematic diagram of the dual plane ERT sensor is shown in Figure 2.

With regard to the main ERT system (Data Acquisition Hardware), this study employs Fast Impedance Camera system (FICA) (or a high performance dual-plane electrical impedance tomography system), the software and hardware of which have been enhanced and consolidated by OLIL group (Online Instrumentation Laboratory/University of Leeds). It is worth pointing out that one of the advantages of this system is the efficiency of the hardware and simplicity of the operation of the control software. The principle of the hardware operating system and the operation of the control software is described in detail in [19].This development of the conventional EIT system could be considered as a response to the requirement of many industrial processes such as two/multiphase flow, where a higher (faster) frame rates is required to measure and monitor the flow behavior. The Data Acquisition System (DAS) is based on the phase sensitive demodulation and both the amplitude and the phase of the measurement can be obtained. Once the system is connected it allows the Data Acquisition System to operate in two modes, continuous (on-line) and block mode.

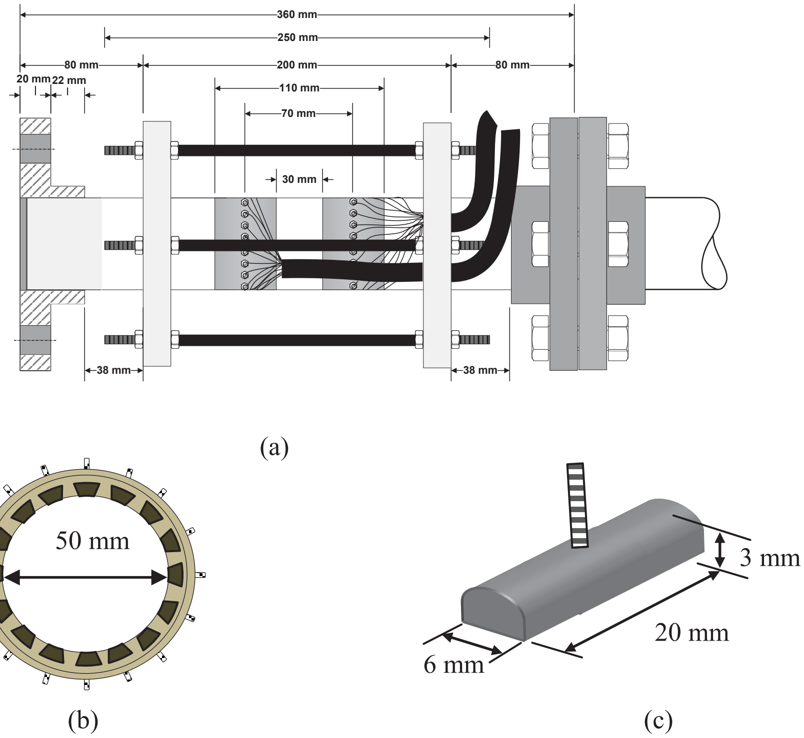

Fig. 2. (a) dual-plane ERT sensor section. (b) 16 electrodes flush mounted at the periphery of the sensor ring (c) A single stainless steel electrode

In continuous mode, a single frame of data for one or two planes is acquired, captured, transferred and displayed in the selected format. This mode can capture data at a frame rate up to 50 dual-frames per second (dfps), which is equivalent to 20 ms; whereas block mode can capture data up to 8000 frames at a rate up to 1000 dfps. At the end of acquisition of each data block, it is then transferred and read by the PC, where it is processed and can be visualized or saved on an external hard drive for later analysis. The image reconstruction system can produce images for both amplitude and phase of the domain, by using one of the versions of Linear Back Projection (LBP) algorithm, which is called Sensitivity Back Projection (SBP) algorithm. The reconstruction algorithm (SBP) can provide further option of displaying images for real and imaginary part.

In this study an alternating current of 15 mA with a frequency of 9600 Hz was injected. After mapping the conductivity of the media through each plane, the conductivity data was converted into the local concentration distribution using Maxwell relationship. Then the signals of the two planes were cross-correlated, using pixel-to-pixel correlation, to estimate the axial solids velocity profile. This implies that the velocity of the dispersed phase (sand) can be estimated by direct cross-correlating the signals obtained from the two sensor planes. The principle of cross-correlation is shown in Figure 3, where L is the distance between the two planes, T is the delay in cross-correlating vector, which is used for estimation of the velocity. The cross-correlation method, pixel-to-pixel, have been used in a number of previous studies [20, 13, 21, 22, 11], although the meaning of cross-correlation has always been argued.

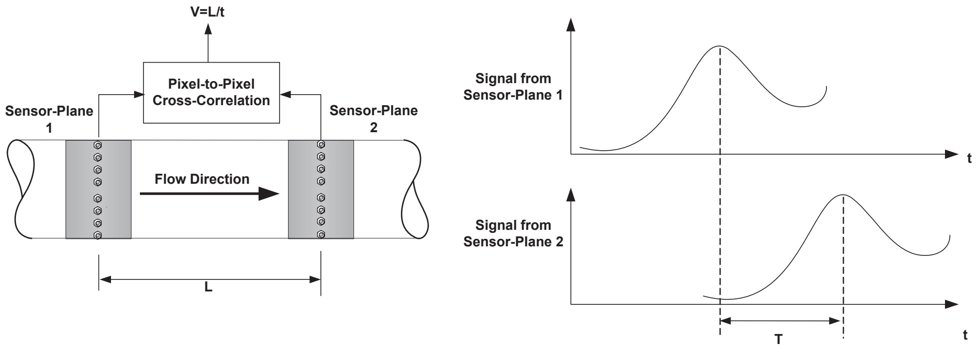

Fig. 3. Principle of cross-correlation for solids axial velocity measurement

2.2. Solids volumetric concentration measurement

In order to monitor the internal structure of the flow two-dimensional concentration profile of the local concentration were calculated across the pipe cross-section. Obviously the local chord concentration can represent a clearer picture of the distribution of solid particles and their movement in the vertical axis of the pipe cross-section. The Fast Impedance Camera System (FICA) was used to measure and collect a set of block data of 8000 frames for each mixture velocity. The measured conductivity data was then entered into the P2000 software to produce the conductivity map of the pipe cross-section. The conductivity map then imported into the software package called AIMFLOW, which stands for Advanced Imaging and Measurement for Flow, Multiphase Flow and Complex Flow in the Industrial Plant. The mean local concentration was produced by averaging a block of frames from the concentration map, and the solids concentration profile was extracted along the vertical centerline of the tomograms generated, which composed of 20 pixels. The height of each pixel was calculated as 2.5 mm for 50 mm diameter pipe. The tomograms reconstructed for each test were collected and analyzed to determine the mean solids concentration and solids concentration profile across the vertical plane of each tomogram.

2.3. Solids axial velocity measurement

To obtain the solids axial velocity distribution, FICA system was used in conjunction with the cross-correlation method. The data was acquired at a rate of 1000 frames per second for each plane. The measurements were taken and a set of block of 8000 dual images were reconstructed for each flow condition. Each dual image represents the conductivity distribution at the upstream and downstream planes at a particular time. Then the relation between the two signals from the two planes was established using pixel-to-pixel correlation method, which has been developed into a software package (AIMFLOW) at the University of Leeds and Chinese Academy of Science. By importing the conductivity map, produced from the ITSP2000 software, into the AIMFLOW, the axial solids velocity, concentration and solids volumetric flow rate can be computed.

2.4. Slurry flow loop

A schematic diagram of the open flow loop used in this investigation is shown in Figure 4. The length of the horizontal and vertical test sections are approximately 7 m and 5 m respectively. The major components of the loop are 50 mm PVCu pipeline, 500 liter mixing tank, a centrifugal pump, which was connected to a digi-drive frequency converter, an electromagnetic flow meter to measure the superficial velocity, four pressure transducers at horizontal and vertical test sections, a thermocouple to monitor the slurry temperature, a diversion flow system with a measuring tank (sampling vessel), two dual-plane ERT sensors, which was connected to the FICA system. The slurry consisted of a mixture of water and a non-uniform shape and size sand with density of 2650 Kg/m3. Based on particle size, two sands were used, with loading concentration up to 10% (v/v) for each of them. Using the particle size distribution curve it was found that sand 1 has a particle size range between (75-700 μm) with d50=240 μm and d85=440 μm. Therefore, sand 1 was classified as medium narrowly graded sand. With regard to sand 2, it was found that its particle size lying between (75-2200 μm) with d50=560 μm and d85=2200 μm, then sand 2 was classified as coarse broadly graded sand. The average superficial velocities were in the range of 1.5-5 m/s. A transparent pipe section of 1 m long was included into the horizontal section, which would enable visual observation of the flow and capturing photographic images.

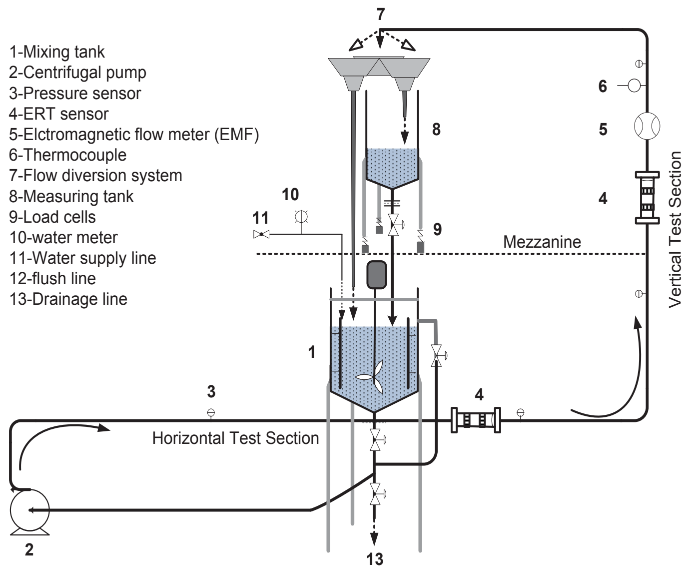

Fig. 4. The schematic diagram of the flow loop

A set of experiments were carried out with different loading solids volumetric concentration, 2% (v/v) and 10% (v/v). After adding the required sand, the slurry was well agitated in the mixing tank in order to achieve a homogeneous mixture. The slurry was initially introduced to the flow loop via the flush line, so as to lubricate the flow loop and allow the flow of solids to progress gradually. After approximately 1-2 minutes the mixture allowed to flow through the discharge point at the bottom of the tank. The flow was first established at the highest velocity of the pump, which was controlled via the digi-drive frequency converter, then reduced gradually from 5 m/s to 1.5 m/s. The reason for that was to cover all the flow regimes occurring in slurry flow.

However, this condition could not be attained for pseudo-homogeneous flow regime, especially for flow of 10% coarse sand, due to the limitations imposed by the pump capacity. Particular attention was paid to carry out every test at steady state condition, by continuously observing the pressure signals (graphs) on the lab-view panel. The ERT measurement then carried out for each condition along with recording the pressure, temperature and mean slurry velocity on the lab-VIEW. Each test measurement carried out for horizontal flow was immediately followed by a vertical flow measurement, in order to investigate the effect one on the other. After each ERT measurement the sampling measurement were carried out by diverting the flow to the pre-calibrated sampling vessel for a very short period of time, after which the level of slurry in the sampling vessel and its weight were recorded. Three pre-calibrated load cells, on which the sampling vessel was standing, were used to estimate the weight of the diverted slurry (sample). The reasons for using flow diversion system was to validate the mean slurry velocity obtained from the EMF, to validate and compare the local concentration obtained from the ERT, to validate solids axial velocity obtained from the ERT and cross-correlation technique and finally to estimate the delivered solids concentration at the discharge point.

2.5. Flow diversion technique

The flow diversion system consisted of using a switch system (or diverting system) and a sampling vessel, which was mounted on a set of three calibrated load cells. The flow switch system was coupled to the sampling vessel at the exit of the flow loop, through which the slurry would return to the mixing tank. The bottom of the vessel has a conical shape, so as to facilitate the sliding of the solid particles at the bottom once the discharge valve is opened for the slurry to return to the mixing tank. The sampling vessel was connected to the mixing tank through 100 mm PVCu pipe. In order to measure mean slurry velocity, the flow was diverted to the sampling vessel for any given length of time. Obviously, during the diversion process, the valve at the outlet of the vessel has to be closed. A level graded glass tube was also mounted on the measuring vessel, through which the diverted slurry level could be monitored. An electronic stop watch was used to measure the duration for which the flow was diverted. However, a great effort was made to carry out the diversion process within a possible shortest time. This is due to two reasons, firstly so as to avoid settling solid particles at the bottom of the vessel, which could be a potential risk for blockage at the discharge point of the sampling vessel. Secondly, taking a given amount of slurry from the system would result in decreasing the suction head of the pump, which precipitate the instability of the flow. The procedure of this method was to divert the slurry and allow a sufficient time for the slurry to reach a certain level, somewhere 50% of the measuring tank. Then switch the flow back to the mixing tank and record the slurry level and the duration of the diversion. As the cross-section area of the measuring tank was known, then the volume of the diverted slurry could be determined as well as the flow rate. After several seconds of diverting the flow to the measuring tank, it was noticed that the velocity shown on the Electromagnetic Flow Meter (EMF) was gradually dropping. Therefore, the reading of the Electromagnetic Flow meter was recorded just before the slurry diversion. Although it was noticed that the EMF readings were slightly fluctuating, the velocity shown of the EMF just before the diversion was considered for the comparison process. As slurry flow is quite complex by nature, then this fluctuation is well expected. Both mean volumetric concentration and mean solids velocity from the ERT and the flow diversion technique was then collected for the comparison, as shown in "Results and Discussion" section. It is worth mentioning that the validation of the local concentration using this technique could not be applied for all transport velocities, particularly low velocities, in horizontal flow, due to particle deposition at lower velocities. As at higher transport velocities the local concentration at any section of the flow loop is more or less the same. Therefore, the local concentration in horizontal flow was validated only for flow of high transport velocities (4 m/s and above).

3. Experimental results and discussion

3.1. Horizontal flow

3.1.1. Solids volumetric concentration profile

Figure 5 showing the tracking of solids concentration changes as a function of transport velocity for medium and coarse sand particles.

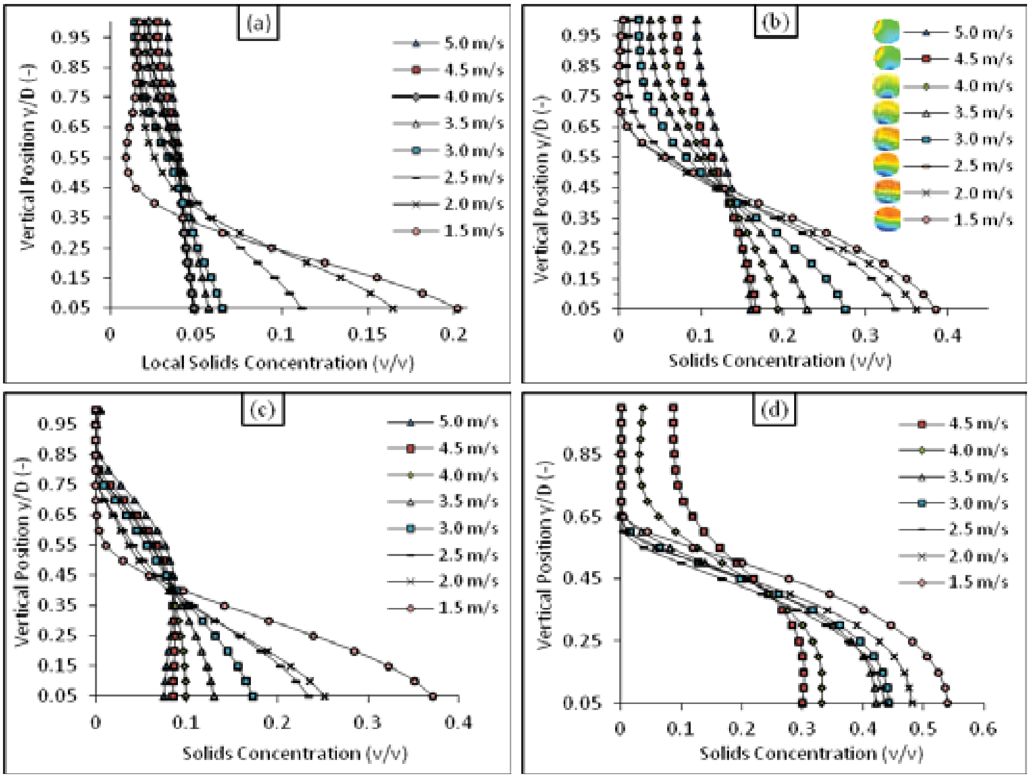

Fig. 5. Concentration Profile as a function of transport velocity for (a) 2% throughput concentration/medium sand, (b) 10% throughput concentration/medium sand; the tomograms are showing the distribution of solid particles at a given transport velocity, (c) 2% throughput concentration/coarse sand, (d) 10% concentration throughput/coarse sand

In order to determine the effect of concentration along with the particle size, two different loading concentrations were used for each sand, 2% and 10%. The X-axis represents the dimensionless vertical position (y/D) inside the pipe, while the y-axis represents the local volumetric solids concentration. It can be noticed that, at low velocities (below 3.5 m/s) most of the profiles composed of a convex (left-hand bend) curve in the upper part of the pipe and concave (right-hand side) curve in the lower part of the pipe. This behavior can easily be noticed for all conditions, except for 2% medium sand, for which the distribution of sand particles is rather quasi-homogeneous with asymmetric distribution across the pipe cross section.

It is quite evident that for both sands and conditions the profile goes through a gradual distortion and changes its pattern from pseudo-homogeneous flow pattern to stratified flow with decreasing transport velocity. From the tomograms, shown next to the legend in Figure 5 (b), it can also be seen that the distribution of solid particles varies depending on the transport velocity (i.e. the local concentration increases with decrease of mixture velocity). At higher velocities medium sand particles are fairly distributed across the pipe cross-section and they are in suspension, due to turbulent eddies formed in the suspending liquid. While at lower velocities, especially at 1.5 m/s, the particles clearly move in saltation (roll and tumble over the bed). Similar trend was observed in the case of coarse sand, except that with higher degree of distortion, which was picked up by the ERT. This phenomenon indicating that the coarser particles cannot be suspended by the turbulent eddies in the suspending liquid in the upper region of the pipe. As a consequence the coarse and heavy sand particles occupy the lower regions of the pipe, which results in producing a large shear stress. The effect of solids throughput concentration has also been detected by the ERT. It can be seen that the profiles of 10% throughput concentration, for both sands, have higher degree of distortion than those of 2% throughput concentration.

3.1.2. Solids axial velocity profile

The velocity profile was measured along the vertical diametrical plane of the pipe cross-section at various flow conditions. Along this plane the local solids velocity was measured at 20 locations. It is to be noted that once the mixture conductivity was measured by P2000 software, 20 x 20 grids were selected, and the grid locations falling outside the pipe cross-section were blanked out. Therefore, the number of remaining pixels within the pipe cross-section was 316. The mean solids local velocity was also determined by averaging the values of solids velocity across 316 pixels.

For simplicity, the results of the velocity measurement presented here are limited and confined only to randomly selected sands and various operating conditions. Figures 6 showing the distribution of solids velocity along the vertical plane of the pipe cross-section as a function of mean flow velocity for coarse and medium sand at different throughput concentration. It can be seen that the shape of the profile goes through continuous distortion as the mean flow velocity is decreased. This is due to the fact that, at low velocities the turbulent dispersing force decreases and the carrier liquid is no longer able to maintain the coarser particles, as a result the coarser particles migrate to the lower part of the pipe. This phenomenon causes an increase in solids particle concentration at the lower part of the pipe. It is apparent that at a given transport velocity the higher the throughput concentration is the further distortion in the profile can be observed. This is highlighted in the case of course sand at two different throughput concentrations, Figure 6 (b, c). It can be noticed that with decrease in mean flow velocity the location of peak solids velocity shifts towards the upper part of the pipe, which is the cause of profile distortion. However, it can be seen that the level of distortion is higher in the flowing of 10% coarse sand rather than 2%. As the transport velocity decreases, the gravity force plays its role, in return the solids concentration increases at the bottom of the pipe.

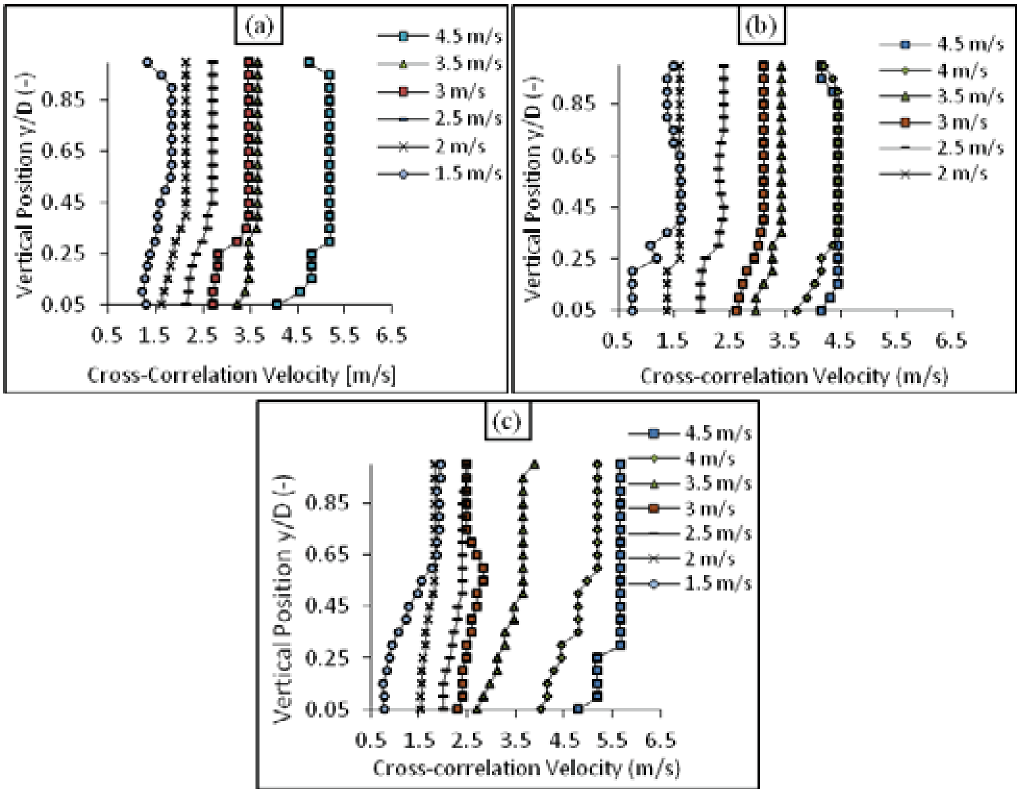

Fig. 6. Solids velocity distribution as a function of transport velocity for (a) 10% throughput concentration/medium sand, (b) 2% throughput concentration/coarse sand, (c) 10% throughput concentration/coarse sand

This increase in solids concentration causes a strong particle-particle interaction, which diminishes the momentum of the flowing solids, as a result the particles at the bottom of the pipe travel slower than those flowing at the top of the pipe. This particular feature of slurry flow, which is clearly highlighted by the ERT, has been the subject of many previous studies [23, 24]. The same trend was observed for medium sand at two different throughput concentrations. Similarly an increase in the degree of asymmetry in the solids velocity profile was noticed to be higher than that of medium sand at the same transport velocity and throughput concentration. This behavior could well be attributed to the particle size effect and has clearly been highlighted by the ERT. Apart from the 2D solids velocity profile, the 3D and vector velocities were also generated by the ERT using a software package called AIMFLOW. After importing the conductivity data acquired by the FICA system and entering several flow parameters for calculation of solids velocity, the reconstructed 3-D solids velocity profile can be visualized on the monitor. An example of the reconstructed 3-D and vector velocities are shown Figure 7. The distribution of solids velocity across the pipe cross-section is shown by a color gradient.

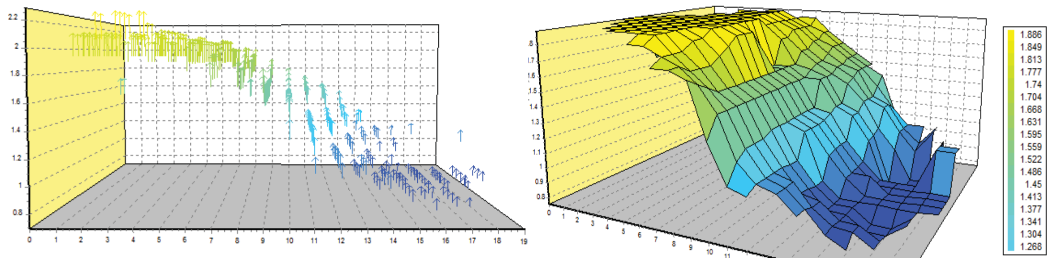

Fig. 7. The 3-D and solids vector velocity distribution for coarse sand at 10% throughput concentration and 1.5 m/s transport velocity. The right hand-side represents the bottom of the pipe, where the solids deposition is highlighted by a blue color, and the left is the top of the pipe

Each shade of color represents the velocity level of the flowing solid particles. The yellow color represents the highest velocity at the top of the pipe, whilst the blue color refers to the lowest solids velocity at the bottom of the pipe. The velocity scale is also indicated by a vertical gradient colored bar on the right hand-side of the profile. However, it was noticed that the 3D profile does not voluntarily provide sufficient information regarding the flow. In addition, for certain flow conditions, the 3D solids velocity profile was associated with noises, which would distort the profile and provide misleading information regarding the location, which had been affected by the noise. The reasons for this may well be attributed to the buried hardware noises. However, this issue will certainly be the focus of further investigation.

3.2. Vertical counter-gravity Flow

The experimental procedure was carried out similar to that of horizontal flow measurement and approximately at the same time. In other words, after each horizontal measurement, consequently a vertical measurement was conducted at various flow conditions. The vertical test section was located directly after the horizontal section and coupled via a 90° short radius bend. The total length of the vertical test section was 5 m from the lower bend. The dual plane ERT sensor was mounted on the vertical section at approximately 3 m from the lower bend to ensure that the flow is fully developed at the ERT location. The Electromagnetic Flow meter was mounted on the vertical line, 1 m above the ERT sensor, to monitor the slurry flow rate through the vertical pipe line. The data obtained for each test was recorded and collected for further processing. The results are shown in Figure 8, in terms of volumetric concentration profile (left hand-side) and solids velocity profile (right hand-side) across the vertical plane of the vertical pipe cross-section. By observing the concentration profiles, it can be seen that for higher sand concentration (10%) the bell-shape (or plug flow) profile can clearly be manifested in the centre of the pipe. This phenomenon has been observed by early researchers [25]. Hence in flowing coarse sand slurry through vertical counter-gravity radial particle migration occurs. The effect of radial particle migration is to move particles into the faster moving streams of the flow. However, the concentration profiles for medium sand suggest a totally different shape in contrast to the concentration profiles for coarse sand.

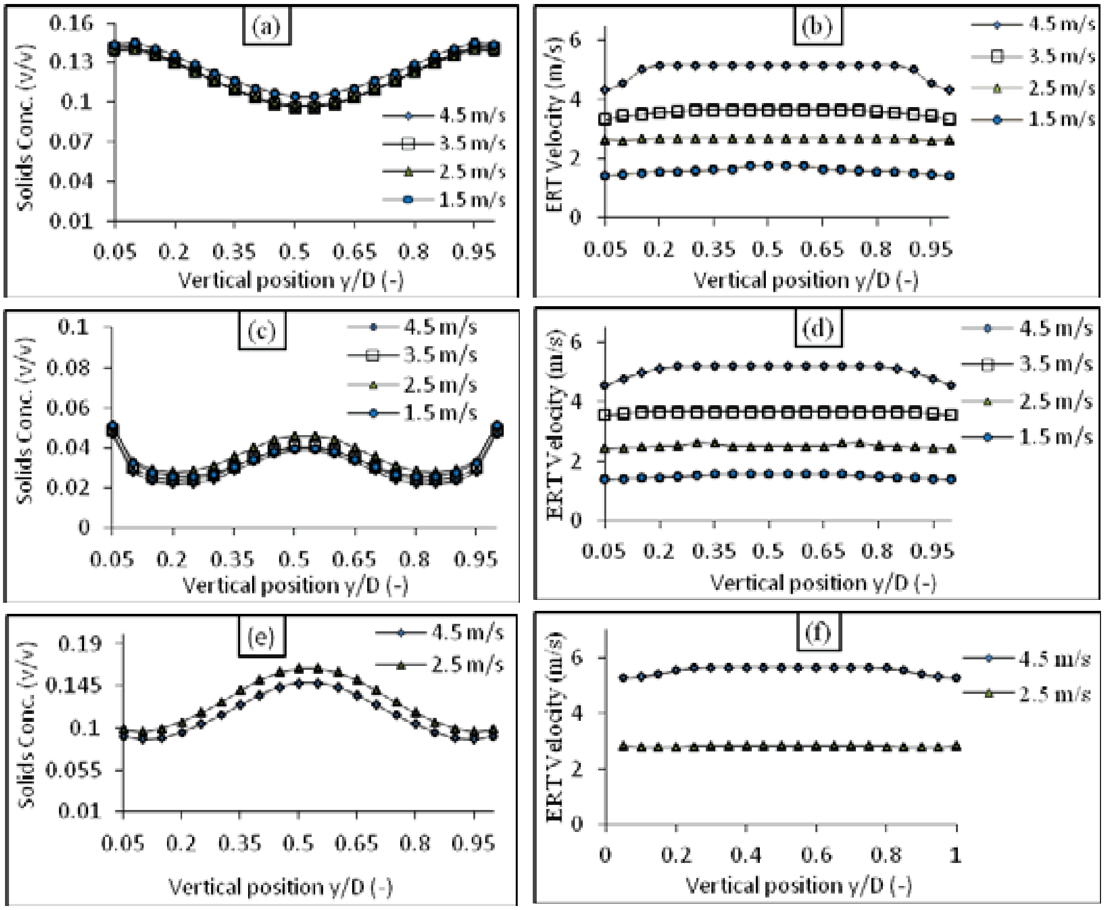

Fig. 8. Concentration profile (left hand-side) and the corresponding solids velocity profile (right hand-side) as a function of transport velocity in upward vertical flow for (a and b) 10% throughput concentration/medium sand, (c and d) 2% throughput concentration/coarse sand, (e and f) 10% throughput concentration/coarse sand

In the case of coarse sand it can be seen that there is a particle-rich core at the centre of the pipe and a particle-lean annulus close to the pipe wall, whereas the phenomenon is vice versa for the flowing medium sand. Based on the ERT results, it can be concluded that the coarse particles move upward the vertical pipe in a plug or core flow pattern, while the medium particles move in annular-like flow pattern. This means that in the case of medium sand the radial particle migration is towards the pipe wall. The phenomenon of annular particle flow has been observed by Karnis et al. [26], who found a particle-lean region close to the pipe wall; however, they observed that for a more viscous carrier liquid the particles move close to the pipe wall. Therefore, it is highly plausible that the very fine particles in the medium sand are accountable for increasing the viscosity of the carrier liquid (water) used in this study. Nonetheless, the condition under which this pattern is formed is not quite clear. Therefore, further work is required to characterize this type of flow pattern in vertical flow. It is also apparent that the phenomenon of radial particle migration for coarse sand is not quite reflected in the solids velocity profile for all conditions, instead showing a blunted shape rather than an inverse bell-shape (or parabolic). The velocity of particles exhibits a uniform distribution throughout the centre region of the pipe cross-section. It is quite expected that the particles within the particle-rich core, for flowing coarse sand, move slower relative to the surrounding layer due to gravity effect (density difference) and particle-particle interaction. The flattened shape of velocity profile has been observed by some researchers, for example Koh et al. [27], similar to the one obtained in this study using the ERT. They also noticed that with increasing delivered solids concentration, the velocity profile becomes increasingly blunted. Their results also revealed another phenomenon, which is as particle size increases the velocity profile become increasingly flattened. This phenomenon was also picked up by the ERT used in this study. Therefore, it can be concluded that the local solids concentration profile and the solids velocity distribution calculated using the ERT are a reasonably accurate representation of the true flow profile for flowing slurry through a vertical counter-gravity pipe in this particular conditions used in this investigation.

3.3. Comparison of the ERT results

The profiles, both concentration and solids axial velocity, were compared qualitatively with actual photograph of the flow, which was taken during the ERT measurements. Figure 9 showing the concentration and velocity profile for coarse sand at 1.5 m/s transport velocity.

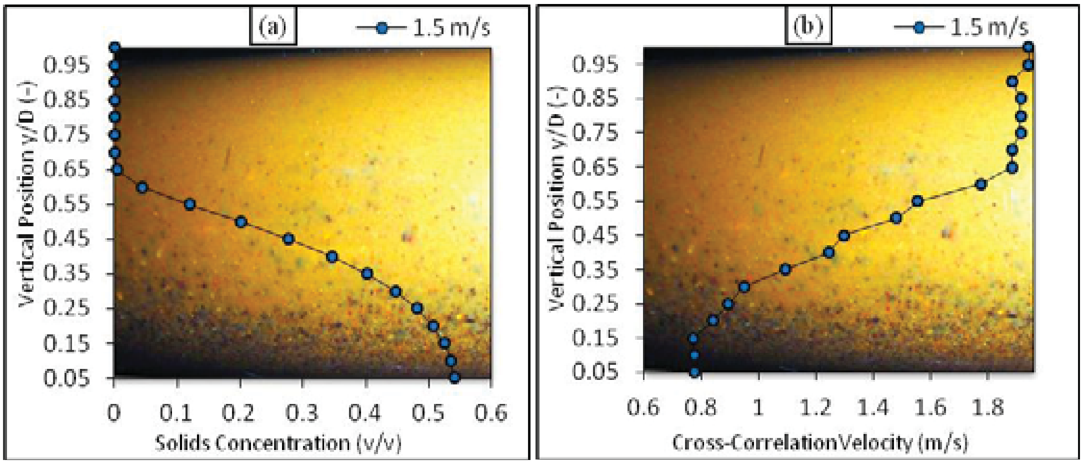

Fig. 9. Concentration profile (a) and the corresponding solids velocity profile (b) for 10% throughput concentration/coarse sand at 1.5 m/s transport velocity in horizontal flow. The background photograph inserted into the plot area, showing the actual image of flowing coarse sand through the pipe, which has been captured at the same time of the ERT measurement

By observing the actual photograph of the flow, inserted into the background of the plot area, it can be seen that a granular bed is formed at the bottom of the pipe with loss particles moving in a sporadic fashion over the bed, whereas at the top of the pipe very few particles can be noticed, moving along the liquid streams and it is clear that they are totally supported by the carrier liquid. On the other hand, the granular bed is identified by the concentration profile and corresponding velocity profile, where a uniform distribution can be seen directly after the concave curve of the profile that extends until it reaches the bottom pipe wall. However, the sporadic movement of particles above the granular bed is clearly identifiable on the both profiles. This is highlighted by the sharp gradient of the profiles, which is due to the difference in the local bed velocity and the turbulent zone at the upper part of the pipe. The high velocity gradient within the lower part of the shear layer causes a chaotic region over the bed, where the particles are lifted from the surface of the bed and supported again by the upward impulses of the turbulent eddies. They can also redeposit on the bed in the absence of fluid turbulence. This phenomenon of sporadic movement of particles continuously occur at the interface between the en bloc sliding (or stationary) bed and the upper turbulent region unless the variation in the transport velocity occurs, which has a direct effect on the lifting force. Also, the upper part of the profile, just on the top of the convex curve, highlights the turbulent region, where some particles are totally suspended in the carrier liquid. The most importantly no gradient within this region should occur, due to absence of slip velocity within this region, as it is shown by the profiles of concentration and velocity. Based on the above observations, it can be concluded that there is a good agreement between the profiles measured by the ERT and the actual photographs of the flow.

The estimated mean solids concentration and mean solids velocity values obtained from the ERT was also compared to the corresponding values measured using the diversion flow technique. This was done by assessing the linear relationship between the results of the ERT and that of flow diversion technique through output results of regression analysis (line-fit), some of which are shown in Figure 10.The line-fit plot showing the relationship between the ERT measured values and the predicted values. The predicted values represent the values obtained from the flow diversion technique and are considered as a reference line for the ERT error analysis. Error analysis of the ERT results have been carried out for various flow conditions, flow orientation, particle size, solids loading concentration and transport velocity.

The results of the error analysis of the ERT concentration in horizontal flow Figure 10 (a, b) revealed that the error is random and a maximum of 19% error was observed throughout the conditions used in this study. It was remarked that, overall, the ERT tends to overestimate the local volumetric solids concentration. As previously mentioned, that the comparison of the ERT concentration with that of sampling vessel was only made at higher velocities, due to settling of particles at lower velocities and accumulation of solid particles locally. Therefore, this overestimation was noticed for both sands mostly at higher transport velocities. This is not a phenomenon that is predicted in settling slurry flow. As at higher velocities the driving force can overcome the resisting force and there is no effect of slip velocity between the liquid phase and the solid phase (i.e. the velocity of the solid phase is equal to the velocity of the carrier liquid). This implies that there is no solids holdup in the pipeline. Therefore, the cause of this error could probably be due to the noise, generated within the FICA system at higher velocities (4 m/s and above). Another possibility is due to the bubbles entering into the flow loop via the mixing tank and adding up into the concentration of the dispersed phase (non-conducting phase). This possibility is based on the fact that at higher velocities the slurry returning to the mixing tank through approximately 2 m length PVCu vertical pipeline (ID=100 mm), at the end of which the slurry falling into the tank and creating a chaotic zone. As a result bubbles are entrained into the tank, whereby they are trapped by the mixing effect and introduced into the pipeline. Although attempts have been made to reduce the acceleration of returning and falling slurry into the mixing tank, some bubbles may still be created and cross the boundary of the mixing effect.

On the other hand the comparison of mean solids velocity obtained from the ERT with that of flow diversion technique revealed that the ERT provides a reasonable estimation of the solids axial velocity in both orientations.

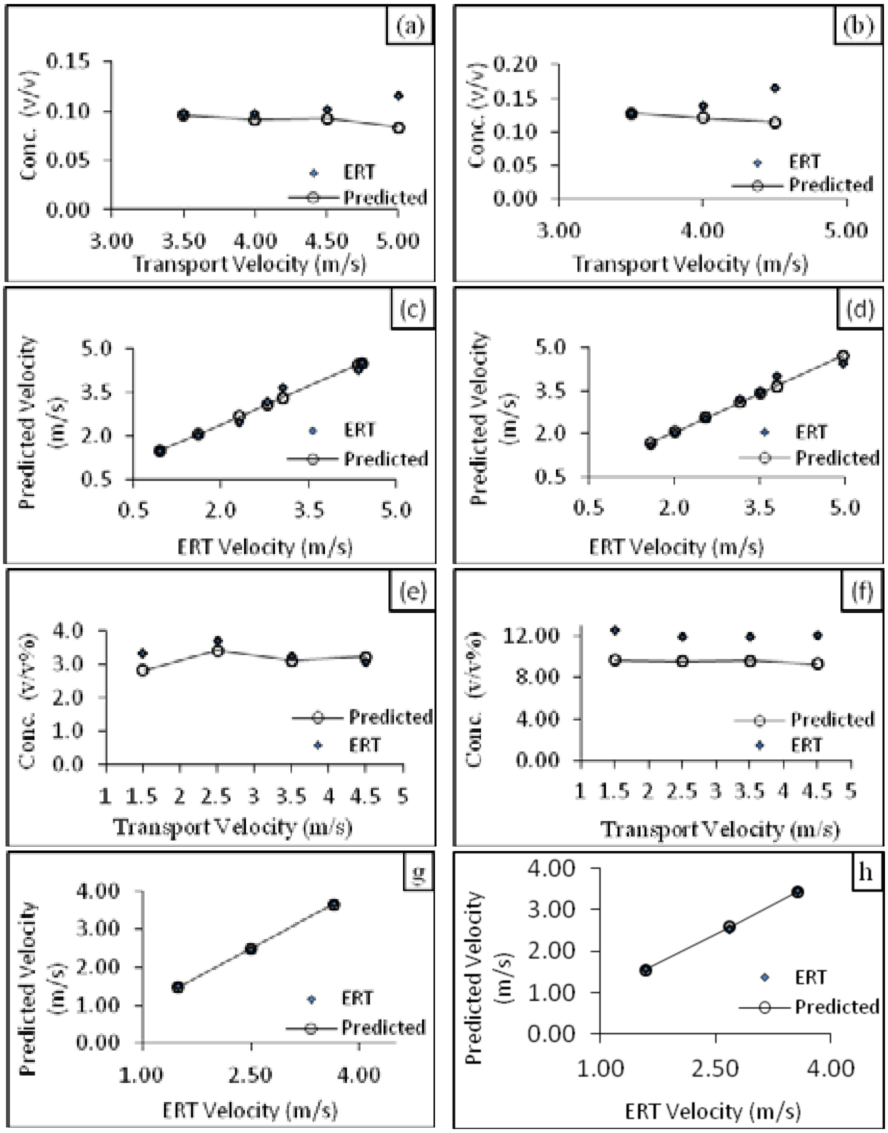

Fig. 10. Comparison of local volumetric concentration and solids velocity obtained from the ERT with that of flow diversion technique at different throughput concentration, particle size and orientation, (a) 10% medium sand/horizontal, (b) 10% coarse sand/horizontal, (c) 2% coarse sand/horizontal, (d) 10% medium sand/horizontal, (e) 2% coarse sand/vertical, (f) 10% medium sand/vertical, (g) 2% coarse sand/vertical, (h) 10% medium sand/vertical1

A randomly distributed error has been noticed with maximum 3.23% for medium sand through horizontal test section, whereas a maximum error 9.25% was remarked for the same sand through vertical line. It is also apparent that the ERT velocities are mostly underestimated at low velocities (3 m/s and below), which is considered as stratified velocity region, where the bed exists and the particles move over it in a sporadic fashion. The reasons for this underestimation have not been established yet. However, this could be due to the instability of the conditions over the bed, where a constant conflict between the driving force and the resisting force exists, as a result of which the saltation and sporadic moment of particles occur. Another possibility is that it could well be due to low spatial resolution of the ERT and sensitivity gradient across the pipe cross-section. An investigation to reveal the reasons behind these deviations will be the subject of future studies. However, it was found that the highest rate of error occurred at high transport velocities (3.5-5 m/s), in which the ERT mostly overestimates the mean dispersed velocity. The cause for this overestimation at such high velocities could again be attributed to the bubbles introduced to the flow loop via the mixing tank. The presence of small bubbles in slurry flow loop has been the cause for measurement errors in previous studies on solid slurry flow [28].

The results of comparison revealed that for the particular flow conditions used in this study, overall the ERT provides a reasonable estimation of volumetric solids concentration and solids axial velocity in horizontal and vertical counter-gravity flow.

4. Conclusions

A high performance dual-plane Electrical Resistance Tomography system (ERT) has been employed to interrogate the internal structure of horizontal and vertical counter-gravity slurry flow. The exceptional capability of this system enabled acquiring high frame rates (1000 dfps) in a non-intrusive fashion. The tomograms reconstructed for each test were collected and analyzed to determine the mean local solids concentration and solids volumetric concentration profile across the vertical plane of the pipe cross-section. While the dual-plane ERT system was combined with the cross-correlation technique to obtain mean local solids axial velocity and solids axial velocity profile. The profiles, solids concentration and solids axial velocity, obtained from the ERT, was compared qualitatively with the actual photographs of the flow, which were captured during the ERT measurements. It was found that there is a good agreement between the two methods. Therefore, it can be concluded that the dual-plane ERT system could well be used for on-line monitoring slurry flow through pipelines. The estimated mean local solids volumetric concentration and mean solids axial velocity values measured by the ERT were also compared to the corresponding values measured using the diversion flow technique. Some deviations were noticed in the mean local concentration obtained from the ERT and have found to be quite random. However, the error analysis of the ERT results demonstrated that, overall, the ERT tends to overestimate the local volumetric solids concentration. The reason for this error was associated to the presence of bubbles in the pipeline. In vertical upward flow, the effect of radial particle migration has been picked up by the ERT system. Based on the solids volumetric concentration distribution across the vertical plane of the vertical pipe cross-section, it was found that the coarse sand flows in a plug or core flow pattern, whereas the flow of medium sand demonstrated an annular-like flow pattern. On the other hand, it was found that the combination of the ERT and cross-correlation provides a reasonable estimation of mean solids axial velocity in both flow orientations. However, the velocities measured in horizontal flow were found to be underestimated by the ERT at low transport velocities (below 3 m/s). Therefore, a future investigation is required to unfold the reasons behind this error. Finally, this study revealed that the high performance dual-plane ERT system can be used for monitoring slurry flow and estimation of volumetric solids concentration and solids axial velocity in horizontal and vertical counter-gravity flow. However, particular attention should be paid to quantitative results obtained at high transport velocities.

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